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DEVELOPMENT OF PREDICTIVE FINITE ELEMENT MODELS FOR COMPLETE CONTACT FRETTING FATIGUE

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Abstract

Nucleation and propagation of cracks under fretting conditions has been a subject of study for many years. An extensive experimental investigation to study these cracks was undertaken by Royal Aerospace Establishment (RAE Farnborough). Of particular interest to RAE was an Aluminium alloy (L65) developed for aerospace applications.

Many researchers have studied fretting damage and fatigue cracks. Some have examined damage development due to wear, whilst others have analysed cracks under linear elastic fracture mechanics (LEFM) domain. To date, no attempt has been made to develop an integrated numerical model which incorporates all aspects of fretting fatigue i.e. nucleation, initial (or early) crack growth, and long crack propagation. The development of such a model is the principal aim of this work. It is expected that the integrated approach will provide the basis for a standard fretting fatigue analysis of other materials, components, and structures using the finite element method (FEM).

This study uses the earlier experimental results with RAE as the reference for comparison. The approach followed is to implement the various stages of fretting in a commercial finite element code, ABAQUS. Unlike previously used simple FE models, both specimen (Aluminium alloy) and the fretting pad (steel) are modelled to simulate the real contact conditions including slip.

Various predictive models for crack nucleation (based on damage) and propagation (based on fracture mechanics) are developed, tested, and implemented in ABAQUS. Results clearly show that these models together provide a good estimation tool for predicting total life in complete contact fretting fatigue. It is envisaged that the integrated model will be easily utilised for other materials, components, and structures subjected to fretting fatigue conditions with minimum experimental testing required.

Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Mohamad Haidir Maslan

January 2016

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Nomenclature

Acronyms

ASTM	American Society for Testing and Materials
ΔMTS	Maximum Tangential Stress Range
EPFM	Elastic-Plastic Fracture Mechanics
FEM	Finite Element Method
FS	Fatemi-Socie
LEFM	Linear Elastic Fracture Mechanics
MERR	Maximum Energy Release Rate
MTS	Maximum Tangential Stress
NTSB	National Transportation Safety Board
SWT	Smith-Watson-Topper

Roman Symbols

a	semi contact width
B	Specimen thickness
b	fatigue strength exponent
c	fatigue durability exponent
D	damage fraction
R	Cylinder radius
2D	two dimensional
P	Normal Load (N)
E	Young Modulus (MPa)
E*	combined modulus (MPa)
$F_{friction}$	Friction load (N)

H	Hardness
J	Strain energy release rate or work input rate (J/m^2)
K_I, K_{II}, K_{III}	Mode I, II, and III stress intensity factors ($MPa\sqrt{m}$)
K_{IC}	Plane strain fracture toughness ($MPa\sqrt{m}$)
N	Normal load (N)
N_f	Life (cycle to failure)
P	contact pressure (MPa)
$p(x)$	contact pressure (MPa)
p_o	maximum normal pressure (MPa)
r_p	Plastic zone size (μm)
S	Sliding distance (μm)
W	rate of wear (m^3/m)
W_s	Work required to create new surfaces

Greek Symbols

v	Poisson Ratio
μ	coefficient of friction
ε_a	strain amplitude
ε_{ea}	elastic strain amplitude
ε_{pa}	plastic strain amplitude
$\varepsilon_f^{'}$	fatigue ductility coefficient
γ	shear strain
σ_a	normal stress amplitude (MPa)
$\sigma_f^{'}$	fatigue strength coefficient (MPa)
σ_{xx}, σ_{yy}, τ_{xy}	2-D stress components in Cartesian Coordinates (MPa)

σ_{rr}, $\sigma_{\theta\theta}$, $\tau_{r\theta}$	2-D stress components in Polar Coordinates (MPa)
σ_y or σ_{ys}	Yield Stress (MPa)
σ_{max}	maximum stress (MPa)
τ	shear stress (MPa)
θ	direction in front crack tip

CHAPTER 1. INTRODUCTION

1.1 Introduction

Fatigue failure was detected as early as 1837. Despite many attempts that have been made to understand and to avoid accidents due to fatigue failure, these failures still continue to occur. In the aircraft industry for example, fatigue failure was the cause of catastrophic accident of the first commercial aircraft de Havilland Comet in 1953[1]. Three aircrafts broke up during mid-flight within one year after the commercial aircraft was launched. Investigations indicated that the main cause of these catastrophic failures was by metal fatigue in the airframes. Windows with sharp corners followed by rivet holes around increased the stress concentration, as shown in Figure 1.1. Lack of knowledge about fatigue at the time contributed to this rather inferior design. These accidents, however, led the company and the competitors to invest more on research on metal fatigue resulting in better and safe design of aircrafts.

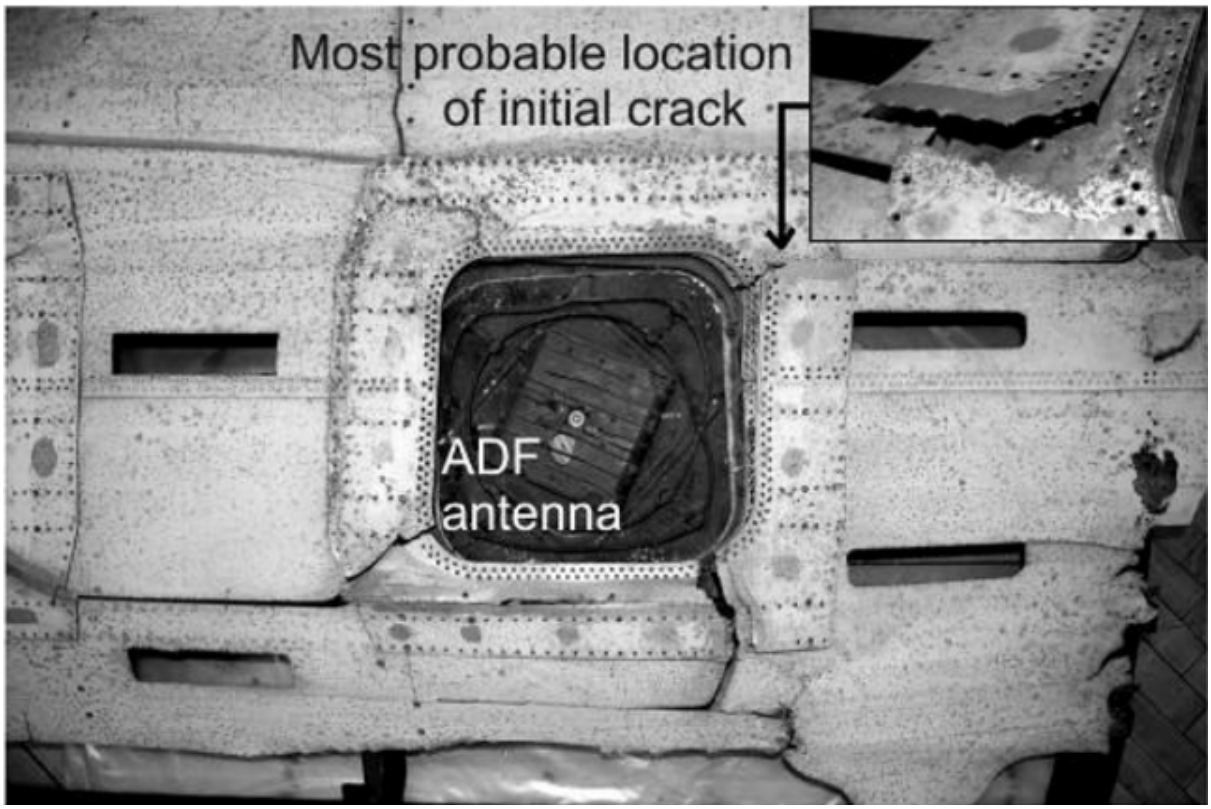

Figure 1.1: Fuselage fragment of Comet [2].

Despite improvements, another fatigue failure involving a rivet joint occurred 35 years later in 1988. A Boeing 737-200 owned by Aloha Airlines, experienced an explosive decompression due to mechanical structural failure during flight. Approximately 5.5 m of the cabin skin and structure of the cabin entrance door above the passenger floor had separated from the aircraft (Figure 1.2).

Figure 1.2: Aloha Airline flight 243 accident [3].

Failure was found to have initiated along a fuselage skin longitudinal lap joint that had been cold bonded and also contained three rows of additional countersunk rivets. Fuselage hoop loads were intended to be transferred through the joint rather than through the rivets. However, some areas of the lap joints did not bond at all, the hoop load transfer though the joint was borne by the three rows of countersunk rivets. The countersinking extended through the entire thickness of the sheet which resulted in a knife edge being created at the bottom of the hole, as shown in Figure 1.3. Stress concentrated at the knife edge and promoted fatigue crack nucleation. For this reason, fatigue cracking began in the outer layer of the skin at a lap joint along the upper and highly stressed row of rivet holes.

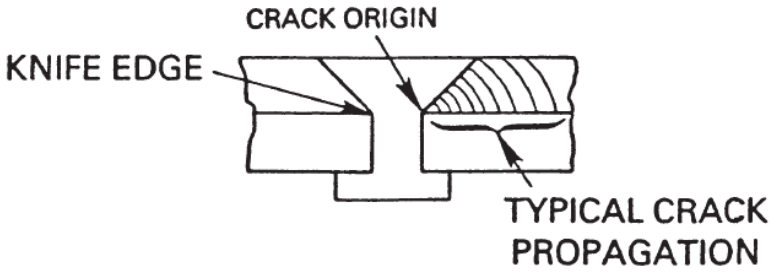

Figure 1.3: Schematic view of a countersunk rivet and the associated fatigue crack observed in Aloha Airlines 737 accident [3]

More recently, in April 2011, a Boeing 737 operating for Southwest Airlines [3] experienced a rapid decompression during flight. The aircraft sustained substantial damage; post-accident inspection revealed that a section of fuselage skin had fractured and flapped open on the upper left side above the wing, Figure 1.4. The entire section of skin remained attached along the lower edge and was deformed outward, as shown in Figure 1.5. The fracture along the upper edge was through the lower rivet row of the lap joint. There was no visible damage to the surrounding frames, stringers, and stringer clips. At National Transportation Safety Board (NTSB) materials laboratory, microscopic examination of the fracture surfaces of the ruptured skin revealed fatigue cracks emanating from at least 42 out of the 58 rivet holes. Non-destructive eddy current inspections were conducted around the intact rivets on the removed skin section forward of the rupture revealed indications of cracks at nine rivet holes in the lower rivet row of the lap joint.

Figure 1.4: Photograph of Southwest airliner with a hole in the upper left fuselage [4]

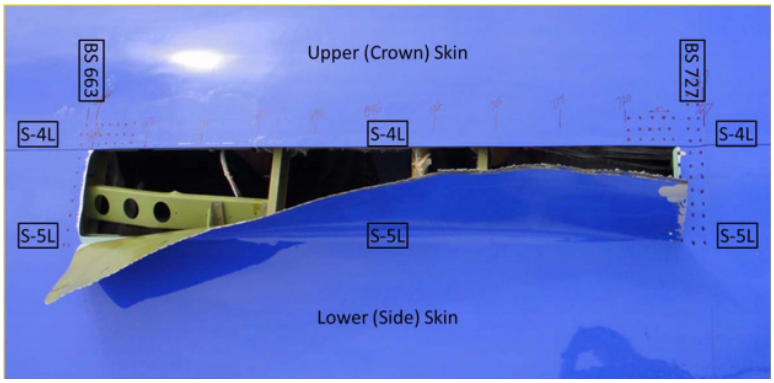

Figure 1.5: Close-up view of the hole in the fuselage side skin [4]

According to NTSB technical report [4], at the inner surface of the lap joint, the rivet holes in the upper and lower skins were found to be slightly offset relative to each other, and many of the rivet holes on the lower skin were not circular but slightly oval. The fracture (fatigue cracks) intersected the majority of the lower-row rivet holes. The corresponding area located at the underside of the expanded portion of the rivets also showed fretting damage consistent with the underside of the expanded portion of the shank rubbing against the plate.

With this simple example, it can be concluded that continuous in-depth study of each accident is necessary. Although accidents may be unavoidable, design improvements can hopefully reduce the chance for such accidents to occur.

1.2 Fretting Fatigue

Fretting is a rubbing process between two surfaces due to oscillatory micro-slip which occurs between them. It occurs in machine components subjected to a clamping pressure and vibratory excitation or an oscillatory tangential force. Fretting damage can be classified into fretting fatigue and fretting wear.

Fretting wear is the result of repeated fretting between two surfaces over a period of time which will remove material from one or both surfaces in contact. In fretting wear, damage is measured by the volumetric material loss.

Fretting fatigue, on the other hand, is defined in terms of the reduction in fatigue strength or fatigue life due to small amplitude movement between contacting surfaces as one of the members is subjected to a cyclic stress.

Fretting fatigue is common in many mechanical systems and engineering structures (for example: aircrafts, spacecrafts, automobile, electrical equipment, manufacturing equipment, human body implants, etc.) which are subjected to variable cyclic loading on the components in contact. There are many practical applications that are subjected to fretting fatigue, such as bolted and riveted connections, bearing shafts, blade-disk attachment in gas and steam turbines and aero-engine splined couplings.

Figure 1.6 shows two examples of fretting fatigue in aircraft machinery components.

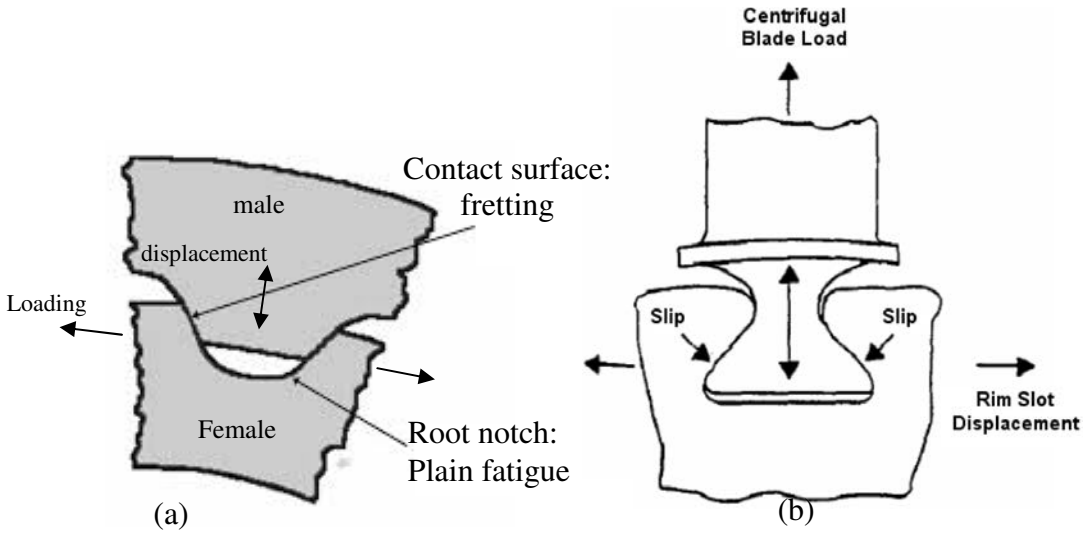

Figure 1.6: fretting fatigue on (a) spline coupling (b) dovetail joint.

1.3 Previous Research

Most of previous fretting fatigue studies have been carried out for aerospace applications where weight and strength are main concerns. The most extensively studied materials are aluminium and titanium alloys as they are used for aerospace structures and engine parts. In the experimental work, these materials are studied in either a bridge or a single pad configuration in complete or incomplete fretting contact. Experimental studies are also carried out on actual components such as rivet joints, dovetail joints and spline couplings.

Besides experimental work, fretting fatigue is also studied using computer simulations. Finite element methods are used to investigate in detail stress, slip, and several other parameters which affect fatigue life. FEM is also used to model crack initiation and propagation in fretting fatigue using critical plane analysis and fracture mechanics. Wear

surface profiles affected by adhesive wear and plastic ratcheting can also be modelled with FEM.

Despite the extensive experimental and modelling work which has been carried out previously on fretting fatigue, it has concentrated mainly on incomplete contact and complete contact has largely been ignored. Although the two types of contact have many similarities, there are several characteristics of complete contact with sharp edges which can cause different tribological effects. Hence, this study intends to include tribological parameters such as wear to improve the current state of complete contact fretting fatigue modelling.

1.4 Overall Aim and Objectives

The ultimate aim of this research is to develop a modelling methodology for predicting fretting fatigue life which includes the tribological aspects of fretting.

The specific objectives are:

- To model fretting crack initiation which includes evolution of surface profile and surface degradation due to wear.
- To model fatigue crack growth of a short crack until fracture by considering multiaxial effects.
- To integrate all the models to produce a total fretting life model in fretting fatigue.

1.5 Structure of report

Following the introduction **(Chapter 1)**, this report is divided into the following chapters:

Chapter 2 Parameters in Fretting Fatigue

This chapter presents a fundamental understanding of the parameters associated with fretting fatigue. It includes contact mechanics, tribology, fatigue, and fretting fatigue.

Chapter 3 Literature Review

This chapter presents a literature review on previous relevant works, discussing state of the art in the field according to scope of this thesis. It consists of contact and failure mechanics